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Economic evaluation of hybrid renewable energy systems for rural electrification in Iran—A case study

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ABSTRACT

The Binalood region in Iran enjoys an average wind speed of 6.82 m/s at 40 m elevation and an average daily solar radiation of 4.79 kWh/m^2/day. Within this perspective, a remote rural village in Binalood region, called Sheikh Abolhassan, can readily be expected to have more than enough potential for its load demand to be supplied with a stand-alone hybrid renewable energy system. Yet the local state-run electrical service provider extended the utility grid to the village in 2006 to boost the already present diesel generator. This study aims, firstly, to explore how economical it would have been to keep supplying the electricity of the village by the diesel generator and add renewable energy generators to increase the renewable fraction of the system. On a second stage, we tried to investigate how renewable energy sources (RESs) can still be added to the current utility grid power supply in Sheikh Abolhassan to achieve a more economical and environmentally friendly system. The software HOMER is used in this study to evaluate the feasibility of various hybrid diesel-RES and grid-RES energy systems. Findings indicated that the addition of renewable power generators to the system both before and after the grid extension could and still can result in a more economical power system, which is obviously cleaner and more climate-benign.

Contents

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1. Introduction

When you need power at a remote site, you seriously have to consider more than just the easiest options before you choose to install a power supply, for otherwise high installation, operation and maintenance costs are the least of your worries. With frequent rises in fuel prices, increasing energy demand, the societies' growing concerns with air and noise pollution, and threatening climate impacts as a result of greenhouse gas emissions, it is no wonder that environment friendly renewable energy sources are rapidly gaining in popularity.

One particularly interesting application of renewable energy systems is installation of hybrid energy systems in remote areas, where utility grid extension is either impractical or prohibitively expensive and where the cost of fuel drastically increases with the remoteness of the location [1]. The term "hybrid" energy system is often used to describe a power system with more than one type of generator, usually a conventional generator powered by a diesel or gas engine, and a renewable energy source such as a photovoltaic (PV), wind, or hydroelectric power generator. In recent years, the use of hybrid renewable energy systems to supply the power demand of various regions especially remote areas has attracted some researchers' attention. In [2], electrical demand of the biggest island of Turkey was analyzed to find out how it could be supplied with renewable energy sources. In [3], the feasibility of adding wind turbines to an existing diesel plant of a village in Saudi Arabia was studied. Another feasibility study is reported in [4], where hybrid energy systems with hydrogen as an energy carrier are evaluated for applications in Newfoundland, Canada.

Hybrid stand-alone electricity generation systems are often considered more reliable and less costly than systems that rely on a single source of energy [5]. In various research papers [e.g. 6,7], hybrid renewable electrical systems in off-grid applications have been shown to be economically viable, especially in remote locations. During recent years, the combined use of renewable energy sources, especially wind and solar, is becoming increasingly attractive and being widely used as an alternative to fossil-fuel energy [1].

Although, in 2009, a mere 0.11 percent of produced electricity in Iran came from renewable energy sources (except hydro), the potentials of renewable energy systems have in recent years been given some favorable attention by the authorities [8]. The mountainous lands of Iran are characterized by unique wind corridors, with an estimated practical wind power potential of at least 6500 MW, according to preliminary studies [8] by Iran Renewable Energy Organization (SUNA), an executive arm of the Ministry of Power. On its fifth Five-Year Economic Development Plan (2010–2015), the government has committed to generate 1650 MW of wind energy to be installed ready for operation by March 2014. This, accompanied by additional solar generation, will allow Iran to meet its target power generation of 5000 MW from wind and solar sources by the end of 2015.

Despite remarkable capacity for rapid expansion of renewable energy generation systems in Iran, it seems that the enormous potentials of these energy sources, especially wind and solar energies, have been seriously underestimated and not yet adequately exploited. To give an example, there are numerous remote areas in the country whose power demands have been supplied by utility extension in recent years in spite of their overwhelming potential for installation of renewable energy facilities. In fact, there seems to be a trade-off between economic logic and political expediency as Iranian parliamentarians pressure the government to extend the utility grid to the remotest areas regardless of the expenses. According to the Forth Five-Year Economic Development Plan [9], the government should have extended the utility grid to all rural villages with more than 20 households by 2007, a plan completed in 2010. An example of such regions is the village of Sheikh Abolhassan which is located in Binalood region, enjoying an average wind speed of 6.82 m/s at 40 m elevation and an average daily solar radiation of 4.79 kWh/m^2/day. The electricity demand of the village was being supplied by a diesel generating system until 2006, when utility power lines were extended to the village.

This study set out to investigate the viability of adding a renewable power system to the then already present engine generators had the utility grid not been extended to the village in 2006. On a second stage, we further explored the feasibility of adding renewable energy generators to the current utility system in order to achieve a more economical and environmentally friendly power supply to support the electricity demand of Sheikh Abolhassan.

In order to determine the optimal renewable energy hybrid system design that can cover the load for Sheikh Abolhassan, the present researchers used the software HOMER (Hybrid Optimization Model for Electric Renewables), which is a computer modeling program developed by NREL (National Renewable Energy Laboratory). According to HOMER Energy, the current license holder of the software, HOMER is "a powerful tool for designing and analyzing hybrid power systems, which contain a mix of conventional generators, combined heat and power, wind turbines, solar photovoltaics, batteries, fuel cells, hydropower, biomass and other inputs" [10]. Analysis with Homer requires input on load data, data on all resources, component types and their specifications, economic constraints and costs, efficiency levels, expected lifetime, etc. This software is the most widely used for purposes of hybrid systems optimization [5]. To provide a few examples, HOMER was employed: in [11] to estimate the potential of renewable energy resources for power generation in Bangladesh through a comparison of different available technologies, in [12] to create optimal renewable energy system designs in Maldives, in [6] to assess the feasibility of hybrid PV–diesel–battery energy systems to supply the load demand of a typical remote village in Saudi Arabia, in [13] to simulate off-grid generation options for remote villages in Cameroon, in [14] to analyze the potential use of hybrid PV–diesel energy systems in remote locations of Malaysia, and in [15] to compare different technologies and potential configurations that might meet the needs of isolated communities in the Brazilian Amazon.

By using HOMER as the simulator software, the present paper tries to address the following issues:

1. How economical would it be if the government, as the electrical service provider, were to keep supplying the electricity of Sheikh Abolhassan by diesel generator and add renewable sources in order to enhance the renewable energy share in the system?



Fig. 1. Location of Sheikh Abolhassan in Iran.

2. If renewable power generators are added to the current utility grid in Sheikh Abolhassan, what will be the gains in terms of economic and environmental concerns?
3. Which hybrid energy system is the most efficient and economical at this scale with regard to net present cost (NPC)?
4. Which hybrid RES configurations would bring about a more climate-benign system for the case under study?

2. Description of Sheikh Abolhassan

2.1. Location and population

Sheikh Abolhassan is one of the remote areas located in Binalood region of Khorasan-e-Razavi province of Iran. The location of this village in Iran is shown in Fig. 1 by a solid black circle. The village is located at 36°12′N latitude and 58°48′E longitude, and consists of 10 households.

2.2. Load profiles of the village and electrification

Sheikh Abolhassan's electricity demand has been supplied by the utility grid installed by Khorasan Regional Electric Company (KREC) through a 20 kV line of 7.3 km since 2006. Although it is possible to use HOMER to simulate the operation of a system by making energy balance calculations for each of the 8760 h in a year, the hourly load profiles of the village was not available for a whole year; therefore HOMER was alternatively used to synthesize the load profiles (with randomness) by entering the values for a typical day. A 3% value was used for both day-to-day randomness and time-step-to-time-step randomness. The only load data of the village which had been recorded were three daily load samples referring to 20.02.2004 for December, January and February, to 20.04.2004 for March, April, May, October and November, and to 20.07.2004 for June, July, August and September. Monthly load profile obtained by the synthesizing process of HOMER is shown in Fig. 2. The average annual electricity and peak load demand are 145 kWh/d and 13.4 kW, respectively, which the power system is required to meet.

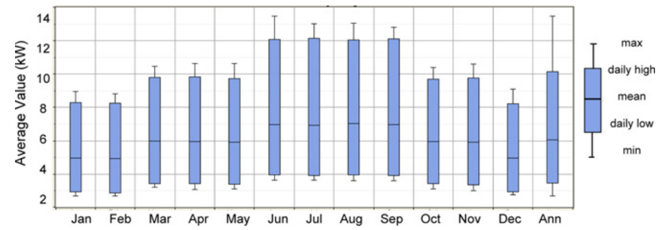


Fig. 2. Monthly load profile.

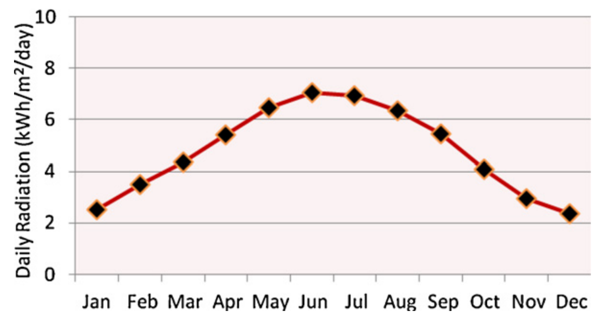


Fig. 3. Average solar radiation data of case study location.

2.3. Availability of renewable energy sources

2.3.1. Solar radiation

Monthly average values of solar data related to the case study location are shown in Fig. 3. As can be seen from this figure, the solar radiation in this village reaches its minimum of 2.38 kWh/m^2/day in December and its maximum of 7.07 kWh/m^2/day in June. So, the average of daily radiation in the whole year is 4.79 kWh/m^2/day.

2.3.2. Wind speeds

Binalood region containing Sheikh Abolhassan is the second windiest region of Iran after Manjil region located in the north of Iran. In this study, wind speed data of Binalood site of Khorasan-e-Razavi province have been used. Although HOMER has the capability to generate synthetic wind data if four parameters "Weibull *k* value, autocorrelation factor, diurnal pattern strength and the hour of peak wind speed" are defined by the user, this synthesizing process is not necessary in this case because the hourly wind speed data of Binallod site are available thanks to the installation of anemometers in this site by SUNA.

Binalood station enjoying Dizbad wind with an average wind speed of 6.82 m/s at 40 m elevation is a very suitable station for installing wind turbines. The average wind speed at 30 m elevation is 6.43 m/s. The lowest monthly wind speed is in January and the highest one in July. Fig. 4 depicts the changes of wind speed from

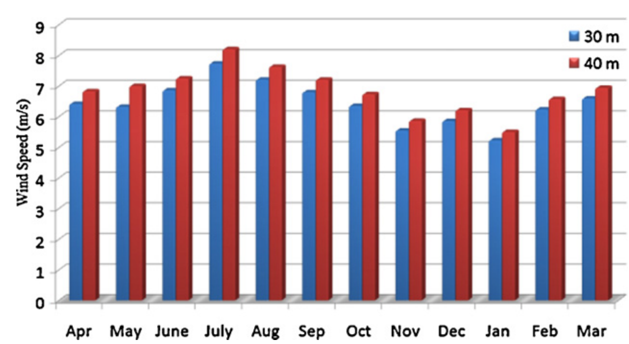


Fig. 4. Average wind speed at Binalood site.

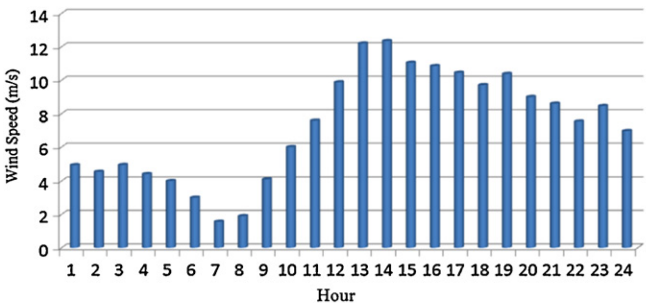


Fig. 5. Wind speed changes at Binalood in 24 h of a day at 40 m elevation.

April 2010 to April 2011 at 30 m and 40 m elevations at Binalood site.

One of the most significant features of Dizbad wind is that it has stronger speed during summer when there is more need for electricity (see Fig. 4). The wind speed decreases around midnight, reaches a minimum in the early morning, then rapidly spirals until it reaches its maximum around noon. Fig. 5, illustrating the changes of Dizbad wind speed on 13 February 2011 at 40 m, verifies this fact.

Fig. 6 depicts the wind velocity duration curve for Binalood site from March 2010 to March 2011 at 40 m elevation. This curve illustrates how consistently the wind has blown in the site under study. While it is possible that the average wind blowing in a site is an acceptable figure, the wind may well be uneconomic if it does not blow consistently enough. Now since the average wind speed in the Binalood site at a height of 40 m is 6.82 m/s, and since the curve shows only a gentle slope around the mean, the wind can be considered to have acceptable blowing consistency and is thus regarded an economic wind.

3. Analysis of the power situation in Sheikh Abolhassan before utility extension

The electricity demand of Sheikh Abolhassan had been supplied by a diesel-only system until 2006, when the utility power lines were extended to the village. To evaluate the extent to which this strategy has been economic for the village under study and in order to explore the viability of improving this particular power system through RES technologies, the software HOMER was used to make economic analysis and rank the feasible systems (i.e. systems which can meet the defined demand load) suggested by the software according to their NPCs. The NPC Method weighs up the costs and benefits of the system for a specified period. Although a particular system might have higher investment costs, it can prove more economical considering its lifetime cost, a total of all other costs relating to a power system over its expected lifetime in addition to the original purchase price.

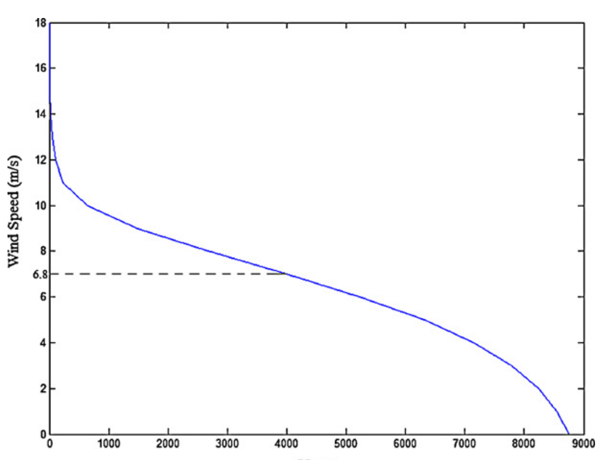


Fig. 6. Wind velocity duration curve at Binalood from April 2010 to April 2011 at 40 m elevation.

3.1. System configuration

In this section, the specifications and configurations of all the feasible stand-alone systems simulated by HOMER for the case under study are described. For an assumed project lifetime of 25 years, the annual real interest rate was taken as 10%. Grid extension and connection costs are important factors for integrating renewable power sources into an existing electricity network [16]. At the present time, the capital and operational costs of grid extension via medium voltage lines in Iran are $20,000/km and $200/year/km, respectively [17]. Grid power price in Iran is on average $0.1/kWh.

3.1.1. Diesel generator

In this study, a diesel generator with a capacity of 15 kW was selected to cover a peak load of 13.4 kW. The operating reserve was set as 10% of the hourly load. The initial capital cost of the diesel generator was assumed $1000/KW. Replacement and operational costs were assumed $900/kW and $0.020/h, respectively. Operating lifetime was also considered 15,000 h. Currently diesel price estimation for remote areas in Iran is $0.32/liter [18]. But as the subsidy of different fossil fuels in Iran is about to be eliminated, this price may increase in the near future.

3.1.2. Photovoltaic array

Considering the market of renewable sources in Iran, installation and replacement costs for a 1 kW solar energy system were considered $6000 and $5000, respectively. In this case five different sizes of PV array (0, 5, 10, 15 and 20 kW) were analyzed. The lifetime of the PV arrays were taken as 25 years and no tracking system was assumed for the PV system.

3.1.3. Wind energy conversion system (WECS)

The wind turbine included in the present analysis is a BWC Excel-S model [19] with a rated capacity of 10 kW and an AC output of 220 V. This wind turbine is connected to the AC bus with obvious advantages in energy efficiency as the produced electricity can directly supply the load without being diverted through the DC bus and storage components [20].

Cost of one unit is considered to be $30,000 while replacement and maintenance costs are taken as $26,000 and $150/year. To allow the simulation program to find an optimum solution, three options were fed into the software for analysis: 0 (no turbines), 1 turbine or 2 turbines. Lifetime of a turbine is taken to be 15 years.

3.1.4. Battery

For the purpose of energy storage, lead acid batteries are included in this analysis for economic considerations. The use of hydrogen as another possible storage alternative is not currently economically viable given the prohibitive costs of electrolyzers and fuel cells and the low efficiency resulting from the electricity–hydrogen–electricity conversion cycle [5]. In this case, commercially available battery models, such as Surrette 6CS25P model (6 V, 1156 Ah, 9645 kWh) [21], were used in the scheme. Cost of one battery was considered $1100 with replacement and operation and maintenance (O&M) costs of $1000 and $10/year, respectively. To find an optimum configuration, the battery bank was assumed to contain any number of 0, 10, 20, 30, or 50 batteries.

Table 1
Categorized optimization results.

					PV (kW)	WECS (number)	Gen (kW)	Battery (number)	Conv. (kW)	Initial Capital ($)	Operating Cost ($/year)	Total NPC ($)	COE ($/kWh)	Renewable fraction
		×			0	0	15	0	0	15,000	17,870	177,208	0.369	0.00
	×	×	×	×	0	1	15	10	10	65,000	14,472	196,361	0.409	0.31
		×	×	×	0	0	15	10	10	35,000	17,894	197,425	0.411	0.00
×	×	×	×	×	5	1	15	10	10	95,000	11,888	202,905	0.422	0.45

3.1.5. Power converter

A power electronic converter is needed to maintain the flow of energy between the AC and DC buses. For a 1 kW system the installation and replacement costs were taken as $900 and $800, respectively. Three different sizes of converter (0, 10 and 20 kW) were fed into the analysis. Lifetime of a unit was assumed to be 15 years with an efficiency of 90%.

According to the components defined above, the energy flow diagram of the system simulated by HOMER is depicted in Fig. 7.

3.2. Optimization results

Based on optimization results performed by HOMER for the defined parameters (see Sections 2.2, 2.3, and 3.1) all feasible systems are categorized by their types. The most economic system in each category is then chosen as the representative of that category. Finally, the selected representative systems from all categories are ranked in order from the most to the least economic. A summary of the results of this procedure can be found in Table 1.

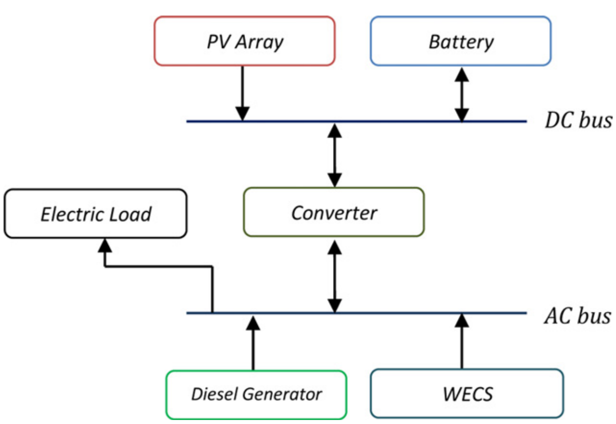


Fig. 7. Energy flow diagram of the system.

3.2.1. Diesel-only

As can be seen from Table 1, a diesel-only system, which consists of one 15 kW diesel generator, in this case, would be the most economically feasible with a minimum total NPC of $177,208 and cost of energy (COE) of $0.369/kWh.

Fig. 8 shows the maximum distance, suggested by HOMER, between the utility power lines and the village in question, Sheikh Abolhassan, which would be economically justifiable for grid extension. At this maximum distance, the NPC of connecting the village to the grid would be equal to the NPC of the previous diesel-only system. As the obtained maximum distance is 5.92 km, and the village was 7.3 km far from the utility grid, it can be safely concluded that, economically speaking, the decision pertaining to grid extension seems to be far from defensible.

3.2.2. Wind–diesel–battery

As Table 1 reveals, the second economically viable system which is also the most affordable one among the feasible hybrid energy systems is the wind–diesel–battery design, which consists of one BWC Excel-S wind turbine, one 15 kW diesel generator, 10 batteries and a 10 kW power converter, with a total NPC of $196,361 and a COE of $0.409/kWh. As can be observed, such a system brings about a renewable fraction (RF) of 31% while the system causes a growth rate of just 11% in total NPC compared to diesel-only system thanks to the excellent wind regime of Sheikh Abolhassan (see Section 2.3.2).

The corresponding maximum distance of economy between the utility grid and the village, suggested by HOMER, for this wind–diesel–battery system is 6.8 km. Since Sheikh Abolhassan was 7.3 km far from the utility grid in 2006, so even if KREC had decided to expand the original system (diesel-only) to the proposed

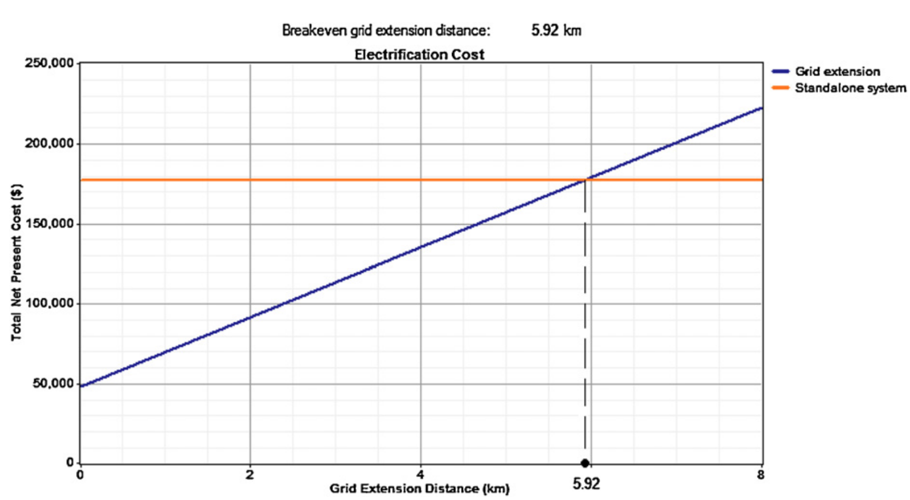


Fig. 8. Maximum distance of economy for grid extension.

Table 2
Categorized optimization results.

[icon]	[icon]	[icon]	[icon]	PV (kW)	WECS (number)	Conv. (kW)	Initial capital ($)	Operating cost ($/year)	Total NPC ($)	COE ($/kWh)	Renewable fraction	Emissions of carbon dioxide (kg/year)
×				0	0	0	0	5292	48,040	0.100	0.00	33,449
×		×		0	1	0	30,000	4323	69,237	0.144	0.31	22,595
×	×		×	5	0	10	39,000	4675	81,440	0.170	0.17	28,387
×	×	×	×	5	1	10	69,000	3706	102,637	0.214	0.45	17,533

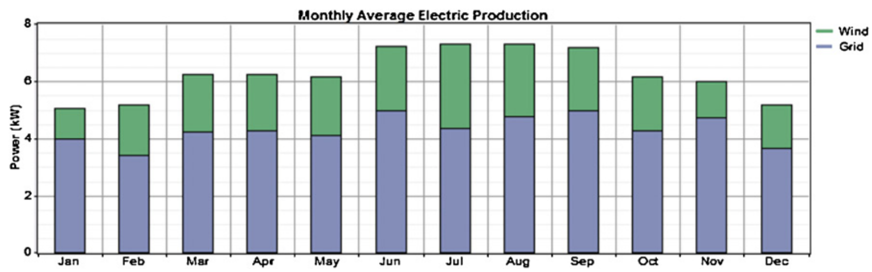


Fig. 9. Share of grid and wind in electric production.

wind–diesel–battery one, it would have been far more economically justifiable compared to the grid extension option.

3.2.3. PV–wind–diesel–battery

As can be obviously noticed from Table 1, the fourth economically feasible system which is the second most affordable one between the feasible hybrid renewable energy systems is PV–wind–diesel–battery design, which consists of one 5 kW PV array, one BWC Excel-S wind turbine, one 15 kW diesel generator, 10 batteries and a 10 kW power converter, with a total NPC of $202,905 and a COE of $0.422/kWh. As can be observed, such a system results in an RF of 45%.

As suggested by sensitivity calculations performed by HOMER, the maximum distance between the utility grid and the village for the PV–wind–diesel–battery system to be economic is 7.1 km. Given the fact that Sheikh Abolhassan was 7.3 km far from the utility grid in 2006, the amazing conclusion is that even if KREC had decided to expand the original system (diesel-only) to the proposed PV–wind–diesel–battery one, they could have expected a marginal reduction in expenses.

4. Analysis of the situation in Sheikh Abolhassan after utility extension

This section aims to investigate how renewable energy sources can be added to the current utility grid in Sheikh Abolhassan to reduce pollutant gas emissions while keeping the system as economical as reasonable.

The components and also their parameters have been assumed like Section 3 with two exceptions: in this system, instead of the diesel generator, it is the grid that is entered into HOMER, and a battery bank is not introduced due to the existence of the grid and economic considerations. The load profiles and the renewable energy sources are the same as presented in Section 2.

4.1. Optimization results

The optimization method performed here is similar to what was explained in the previous analysis (see Section 3.2). Based on the outputs of HOMER for the defined parameters, feasible systems are first categorized by their types. The most economic system in each category is selected as the representative of that category. And finally, the selected representative systems from all categories are ranked according to the lowest NPC. Table 2 presents a summary of the results of this procedure.

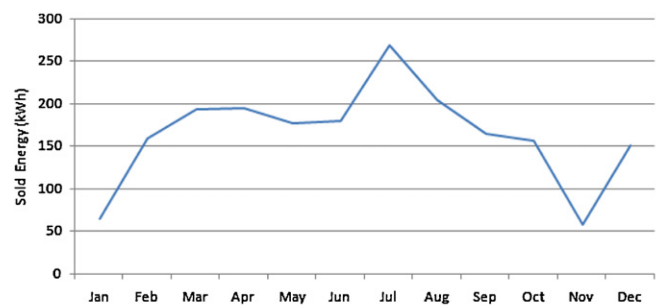


Fig. 10. Monthly sold energy to the grid.

4.1.1. Grid–wind

As can be seen from Table 2, the second most economically viable system which is the most affordable one among the hybrid systems is grid–wind design, which consists of one BWC Excel-S wind turbine, with a total NPC of $69,237 and a COE of $0.144/kWh.

Fig. 9 depicts the share of grid and wind turbine in producing the demand electricity of Sheikh Abolhassan in different months of the year. As can be observed, the share of wind turbines in summer, when the demand load reaches its peak, is more considerable thanks to the amazing feature of Dizbad wind, i.e. the stronger speed during summer.

As can be noticed from Table 2, the grid–wind system causes 22,595 kg/year of carbon dioxide emissions. This means that although such a system causes a growth rate of 44% in total NPC compared to the grid-only system, it brings about an RF of 31% leading to a reduction rate of 32% in emissions of carbon dioxide.

Fig. 10 shows the sold energy of the system to the utility power supply in the year. As can be seen again, the sold energy to the utility is more considerable in summer compared to the values in autumn and winter. The reason is that Dizbad wind reaches its highest speed in summer, when the demand load of Sheikh Abolhassan reaches its peak (see Fig. 2), so the excess produced energy by the wind turbine is sold to the grid.

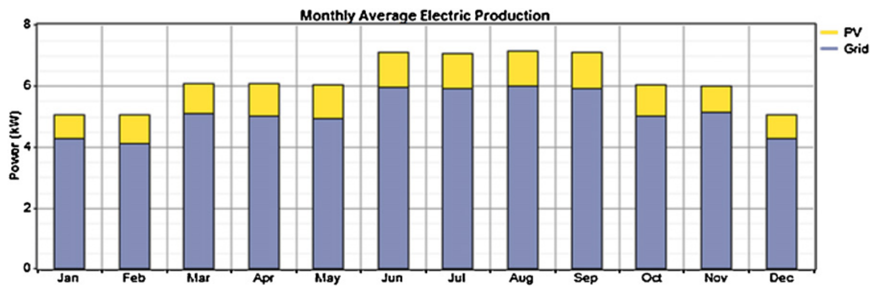


Fig. 11. Share of grid and PV in electric production.

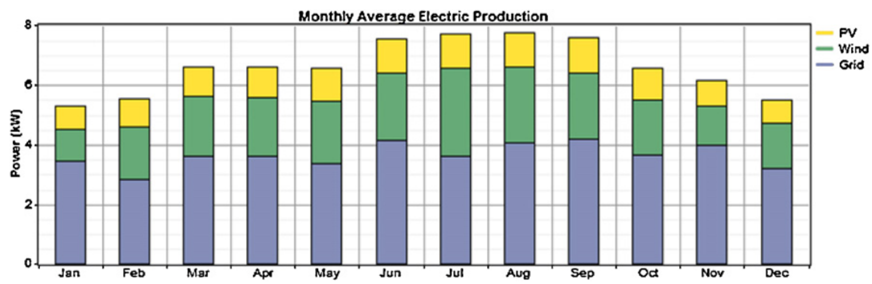


Fig. 12. Share of grid, PV and wind in electric production.

4.1.2. Grid–PV

As can be obviously noticed from Table 2, the third economically feasible system which is the second affordable one among the hybrid systems is grid–PV design, which includes one 5 kW PV array and a 10 kW power converter, with a total NPC of $81,440 and a COE of $0.170/kWh.

Fig. 11 reveals the share of grid and PV in producing the demand electricity of Sheikh Abolhassan in different months of the year. As can be observed, PV produces more electricity in summer when the solar radiation reaches its maximum (see Fig. 3).

It is clear from Table 2 that the grid–PV–battery causes 28,387 kg/year of carbon dioxide emissions. This means such a system not only causes a growth rate of 18% in total NPC compared to the proposed grid–wind system, but it also brings about an RF of just 17% which leads to a growth rate of 26% in emissions of carbon dioxide compared to the grid–wind system. So, the grid–wind system proposed in Section 4.1.1 obviously outperforms the grid–PV one not only economically but also environmentally.

4.1.3. Grid–PV–wind

As can be clearly observed from Table 2, the fourth economically feasible system is the grid–PV–wind design, which contains one 5 kW PV array, one BWC Excel-S wind turbine and a 10 kW power converter, with a total NPC of $102,637 and a COE of $0.214/kWh.

Fig. 12 shows the share of grid, PV and wind energy in producing the demand electricity of Sheikh Abolhassan in different months of the year. As can be noticed, the share of wind turbine in supplying the electricity is more than that of PV in the whole year due to the more suitable condition of the village under study in terms of its wind regime compared to solar radiation potential of this region.

As observed from Table 2, the grid–PV–wind system reduces carbon dioxide emission to 17,533 kg/year, with a reduction rate of 48% compared to that of the grid-only system. The rise in renewable fraction of this system is also very tempting (RF = 45%), but one has to bear in mind that these outstanding merits can only be achieved by nothing less than a 114% rise in total NPC. The grid–PV–wind system might even look much less desirable when we remember that we can obtain a 32% CO_2 emission reduction and a 31% growth in RF with a mere 44% rise in total NPC compared to the grid-only system if we choose to install the grid–wind system suggested in Section 4.1.1.

5. Conclusion

Simulation and evaluation analyses performed in this study supplied convincing evidence to doubt the reasonability of KREC's decision in 2006 to extend the utility power lines to Sheikh Abolhassan. If this state-run electrical service provider had decided to expand the diesel-only system, which supplied the electric demand of the village before the grid extension, to the proposed wind–diesel–battery system or surprisingly even to the PV–wind–diesel–battery system, not only they would have lowered their expenses but they could have achieved a significant rise in the renewable share of the system, which could arguably bring about a less pollutant system.

As for the current state of affairs in Sheikh Abolhassan, simulation results of different proposed systems suggest that wind turbines can still offer some help with 32% reduction in emissions of carbon dioxide and only a 44% rise in NPC.

From all the scenarios studied above, it is readily observed that a lot more can be gained in terms of both economic and environmental concerns if renewable energy sources are taken seriously and are given enough attention when designing power systems.

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